

DIAMOND TURNING IN THE PRODUCTION OF X-RAY OPTICS

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ABSTRACT

A demonstration x-ray optic has been produced by diamond turning and replication techniques that could revolutionize the fabrication of advanced mirror assemblies. The prototype optic was developed as part of the Advanced X-ray Astrophysics Facility - Spectrographic project (AXAF-S). The initial part of the project was aimed at developing and testing the replication technique so that it could potentially be used for the production of the entire mirror array comprised of up to 50 individual mirror shells.

INTRODUCTION

The grazing incidence x-ray mirrors for this project are cylindrical shells consisting of parabolic and hyperbolic sections of revolution. Figure 1 is a schematic of the optic, which is designated as a Wolter I, grazing incidence x-ray reflector. The entire mirror assembly is depicted in the drawing of Figure 2. The optical surface resides on the inside of the shells that have a wall thickness on the order of one millimeter. This geometry, and the number of mirrors required, mandates the use of rapid and accurate fabrication techniques. For this project, several aluminum mandrels were diamond turned with the optical profiles on the outside diameter. Diamond turning is a specialized fabrication process that utilizes precision machines and single-crystal diamond cutting tools. The machine is basically a lathe with a stacked X-Z slide and rotary axis configuration. The motion of the precision slides is monitored using laser interferometer feedback to the controller. This system has a linear resolution of 10 nanometers (less than $1/2$ microinch). The rotary axis is an oil hydrostatic bearing capable of supporting more than 8900 N with a radial error of approximately 100 nanometers (4 microinch). The surfaces produced by this machine have a roughness less than 30 nanometers (1.25 microinch) RMS. To improve this finish, a tool servo system will be implemented. This system will involve piezoelectric actuation and

capacitance gauge feedback. The piezoelectric will be capable of 25 micrometer (0.001 inch) motion at kilohertz bandwidths. This motion will be utilized to actively compensate for the inherent machine vibrations using inputs from the laser system as well as external sensors. The replication technology for the mirror components and the tool servo implementation has the potential to revolutionize the fabrication of precision components. The extremely high precision required of x-ray optics may lead to advances in the manufacturing techniques that could be utilized in the fabrication of other precision components. The key procedures used in the fabrication process and the tool servo development will be presented with the appropriate testing results.

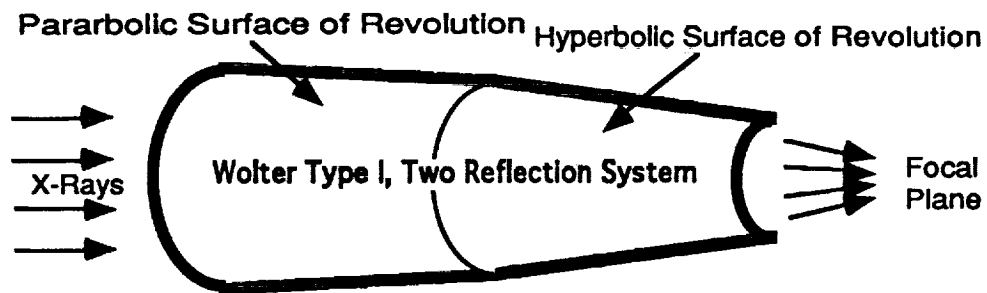


Figure 1 Schematic of the cross section of a Wolter I x-ray optic. The shell is 60 cm long with diameters from 16 to 60 cm. It is formed of 1-mm-thick stress-free nickel with a gold reflecting surface..

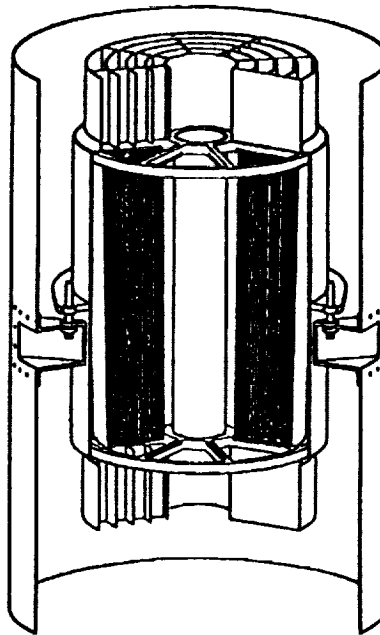


Figure 2 Diagram of the AXAF-S mirror assembly.

DIAMOND TURNING MACHINE

The fabrication process begins with a large aluminum cylinder that will form the core of the replication mandrel. For this project, two aluminum mandrels were formed to the approximate shape on a tracer lathe and then diamond turned with the optical profiles on the outside diameter. The diamond turning machine (DTM) is a Moore Special Tool M-40 Aspheric Generator. This device is capable of turning optical surfaces in ductile materials up to 1.8 meters in diameter. The machine is shown in Figure 3. The linear slide ways are in a stacked configuration with the radial (X) way placed on the axial (Z) way. Both slides ride on precision roller bearings and are driven with DC servo motors and lead screws. The position feedback system is a laser interferometer system with 10 nanometer resolution. The rotary axis typically holds the workpiece and is capable of supporting in excess of 8900 N. The total error motion associated with the oil hydrostatic spindle is less than 100 nanometers.

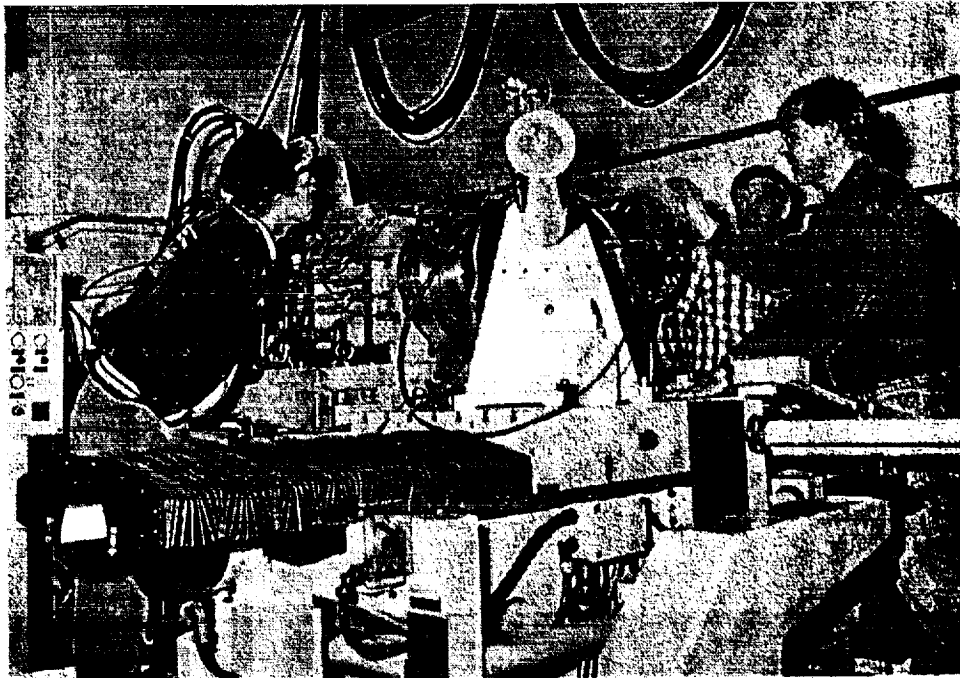


Figure 3 Moore M-40 aspheric generator. The mandrel used to fabricate the full-scale optic is shown attached to the machine spindle. The diamond tool is supported by the large casting in the center of the picture. The radial (X) slide is covered under the bellows in the left part of the picture and the laser interferometer feedback system for the axial (Z) direction is housed in the tube to the right.

The basic components of the mandrel used in the fabrication of the x-ray optic are shown in Figure 4. The body of the mandrel is a hollow aluminum cylinder with approximately 50 mm wall thickness. A tongue and groove mounting system was developed to aid in realignment of the mandrel on the DTM. This system worked well and allowed for centering repeatability to less than 10 micrometers at the end farthest from the spindle. Figure 5 shows a detail of the tongue and groove system. During the initial diamond turning phase, the surface profiles were undercut on the radius by approximately 50 micrometers to allow for the electroless nickel plating. These mandrels were then electroless nickel plated to a thickness of approximately 125 micrometers and re-turned with the aspheric surfaces. These mandrels were then

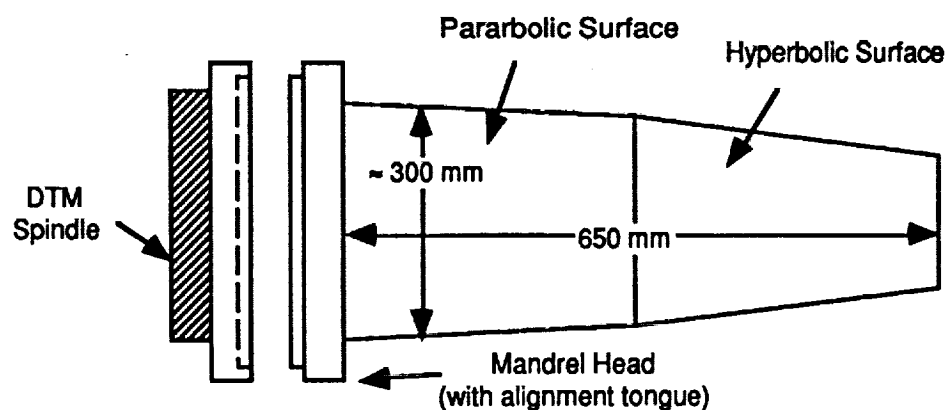


Figure 4 Mandrel for production of Wolter I x-ray reflector.

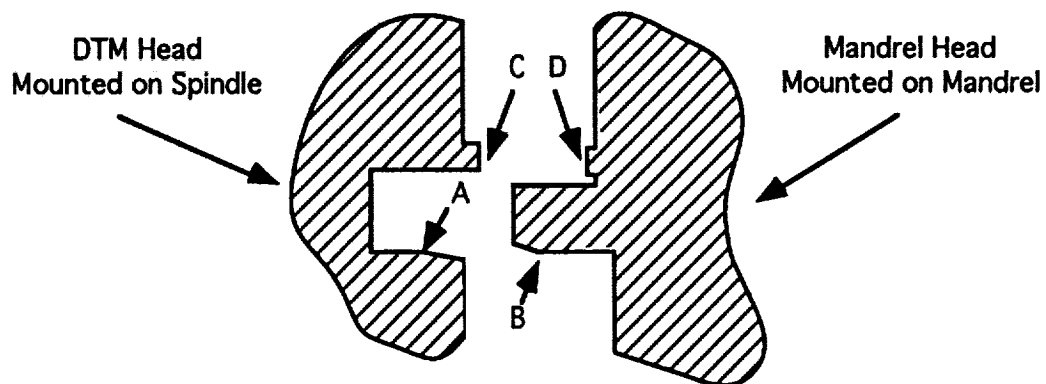


Figure 5 Detail of the tongue and groove used to align the mandrel on the diamond turning machine. The parts mate with a linear contact at points A and B and with a planar contact on surfaces C and D. This system ensured repeatable mounting of the mandrel to the DTM to within 10 micrometers at the far end of the mandrel.

The first mandrel (FS1) had surface finishes after turning that ranged from 30.3 nm (303 Å) RMS on the parabolic surface near the machine spindle to approximately 67.4 nm RMS on the hyperbolic surface at the far end. The average of the measurements was 44.2 nm RMS with a standard deviation of 12.7 nm RMS. Please note that all reported surface finish measurements were made with a Wyko 3D surface finish interferometer at 20X. This corresponds to a measurement area of about 470 by 470 micrometers. An example of this measurement is shown in Figure 6.

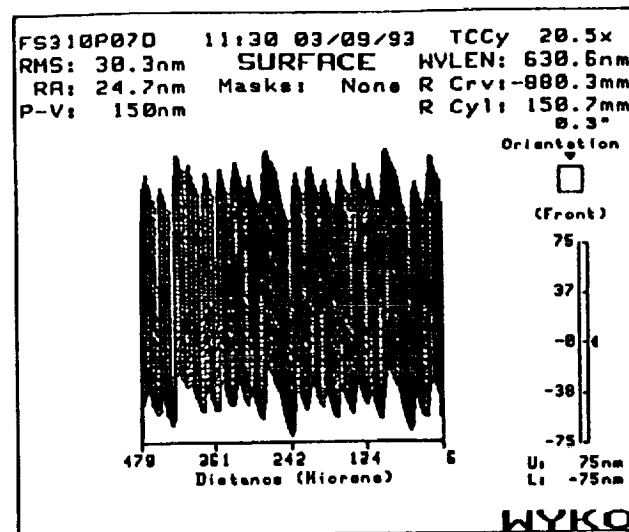


Figure 6 Surface finish measurement of the first mandrel before polishing.

The variation in the surface finish caused significant problems with the subsequent polishing steps. To reduce the finish to the appropriate levels, the hyperbolic surface had to be worked considerably more and the figure accuracy was degraded with the introduction or exaggeration of some mid-spatial frequency errors (10 to 50 mm in length). Also, due to the crossed slide configuration of the DTM, the errors inherent in the axial (Z) slide in the radial (X) direction were not corrected with the laser feedback system. The laser feedback system references the combined axial (Z) motion of both slides back to the metrology frame as was shown in Figure 3. The errors in this direction are therefore measured by the laser system and are corrected for in the controller algorithm. This machine was designed to cut normal incidence optics and only motions in the Z direction are referenced back to the machine's metrology frame with the laser system. Motions in the X direction are referenced as relative motions of the X slide assembly with respect to

the Z slide and are not tied back to the metrology frame. Therefore, the waviness in the X direction of the Z slide remain undetected by the feedback system and are not corrected by the controller. To alleviate this problem, a map of the repeatable waviness error of the Z slide was made using a straight edge reversal technique [1,2]. This error table was subsequently used to correct the cutting path for the second mandrel (FS2). Figure 7 depicts the repeatable way errors for the X direction of the Z slide.

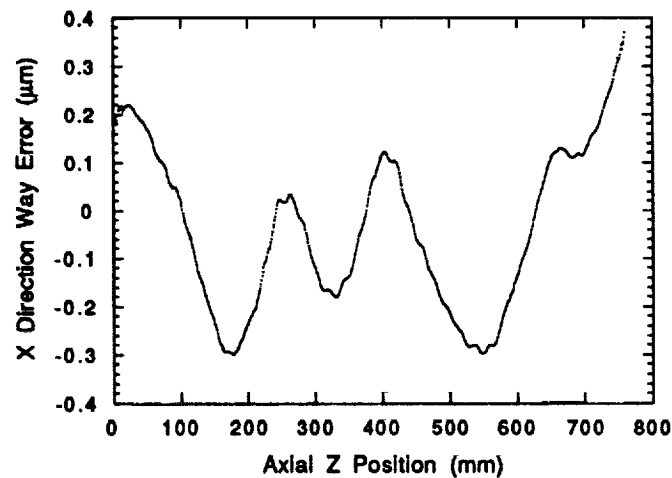


Figure 7 Uncorrected way error in the X direction of the Z slide.

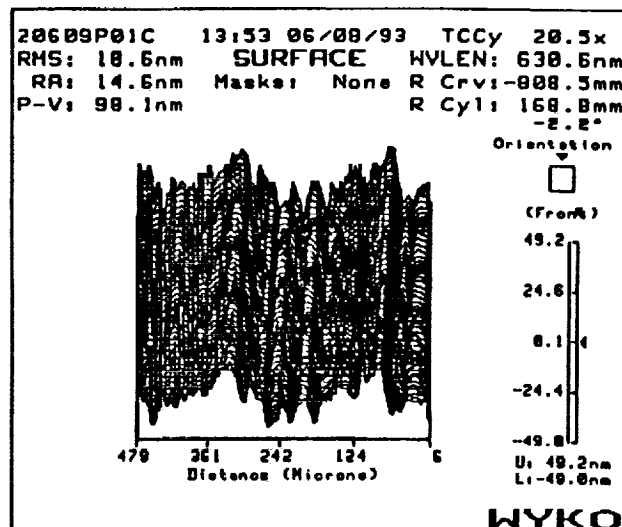


Figure 8 Surface finish measurement of second mandrel after passively limiting the inherent machine vibrations.

Initially, an attempt was made to improve the surface finish by limiting the inherent machine and part vibration for the second mandrel (FS2). This was achieved by altering the spindle speed and using modeling clay as a damping compound inside the mandrel. These changes made a significant improvement in the *as cut* surface finish on FS2. The RMS surface finish readings were much more consistent over the length of the part and ranged from 14.7 nm to 41.3 nm. The average of the measurements was 26.9 nm RMS with a standard deviation of 10.2 nm RMS. An example measurement is shown in Figure 8. This improvement made the polishing operation much easier and resulted in a more accurate overall figure.

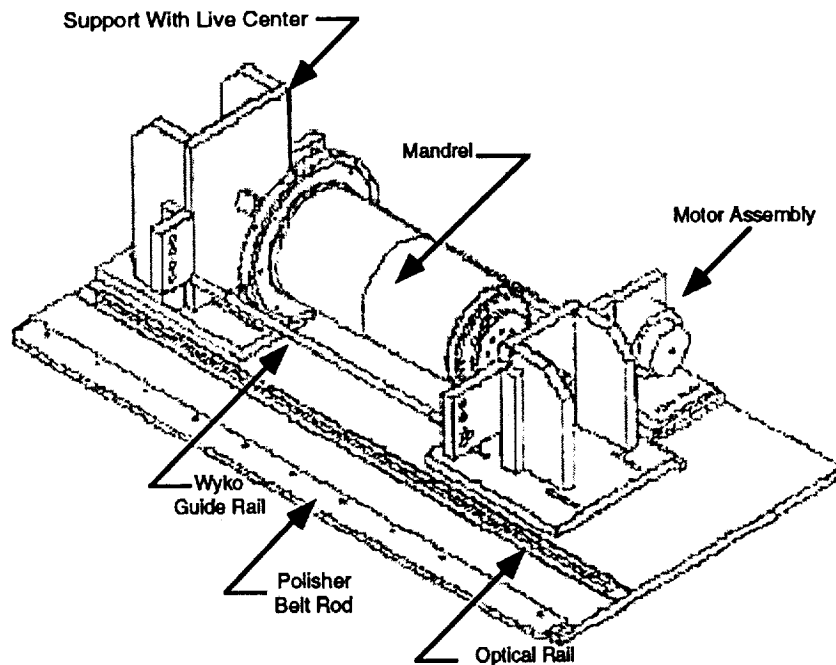


Figure 9 Machine built for polishing the full scale mandrels.

POLISHING

The mandrels are polished to the required surface finish on the specially built polishing machine depicted in Figure 9. The polishing compounds were colloidal silica and aluminum oxide. The surface finish of FS1 after polishing ranged from 1.5 to 2.0 nm RMS. For FS2, the results were much improved and the nominal readings were in the 1.0 to 1.5 nm RMS range. Figure 10 shows a typical surface finish after polishing. Because of the rudimentary design of the polishing arm of

the machine, the automated slide was discarded and the surface was finished by hand. This resulted in a time-consuming process that altered the figure. For future projects, the polishing machine will be upgraded and will include computer control that will systematically polish the mandrel to improve the surface finish. The algorithms for this machine will be developed from empirical polishing data and should be able to reach the desired surface finish characteristics without significantly altering the overall figure of the optical surface. This will be achieved by continuously monitoring the polishing pressure and position to ensure uniform material removal. The optical figure will then be a deterministic function of the accuracy of the diamond turning.

Initially, the figure of the mandrel was measured using a Zeiss coordinate measuring machine (CMM) with a 100-nm resolution. An example measurement is shown in Figure 11. The scatter in the data is apparent and the accuracy of the figure can not be verified to better than a micrometer utilizing this data. Also, the contact nature of the CMM causes defects in the surface of the mandrel after the measurements are made. Figure 12 shows an interferometric scan of the "dimple" left in the surface of the electroless nickel covered aluminum. This defect is about 250 nm deep and is significant when compared to the wavelength of the reflected x-rays. Due to the measurement noise and contact nature, this device proved inadequate and an alternative figure measuring device was considered. The second device chosen for determining the figure of the finished mandrel after polishing was called the Long Trace Profiler (LTP). This instrument was developed by Continental Optical Corporation and uses an optical, non-contact, slope measurement system [3-5]. The second mandrel (FS2) was taken to their facility in Hauppauge, New York, for measurement of the resulting figure after polishing was completed. This device proved quite repeatable and had a much finer resolution (reportedly around 1 nm RMS over the 1-m path). Figure 13 shows the five measurements made on the parabolic end of FS2 with the global curvature and slope removed. This plot is a map of the mid-spatial frequency errors left on the mandrel. These mid-frequency errors are a problem when the optic is used to focus x-ray. Errors of this type tend to scatter the x-rays and blur the focus. The goal of the project is to produce an optic that exhibits 100 arc second resolution at x-ray energies to 10 keV. The mid-frequency deviations shown in Figure 13 may circumvent the attainment of that goal. To eliminate these errors, the inherent machine vibrations must be significantly reduced by either passive or active damping methods.

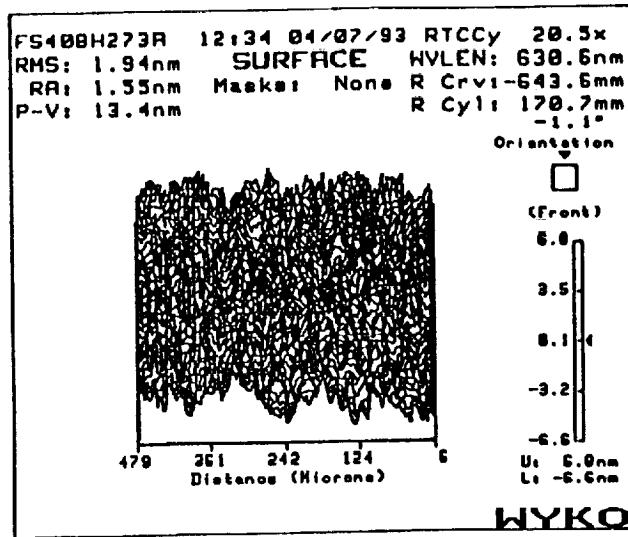


Figure 10 Surface finish measurement of mandrel after polishing.

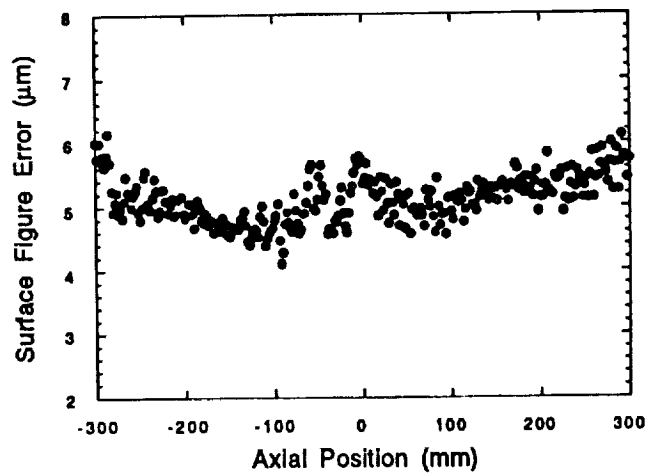


Figure 11 Surface figure measurement of mandrel from the CMM.

15:26 03/15/93 TCCy 20.5x
 RMS: 28.3nm SURFACE WVLN: 630.6nm
 RA: 14.9nm Masks: None R Crv: -976.8mm
 P-V: 241nm R Cyl: 178.9mm
 1.0°

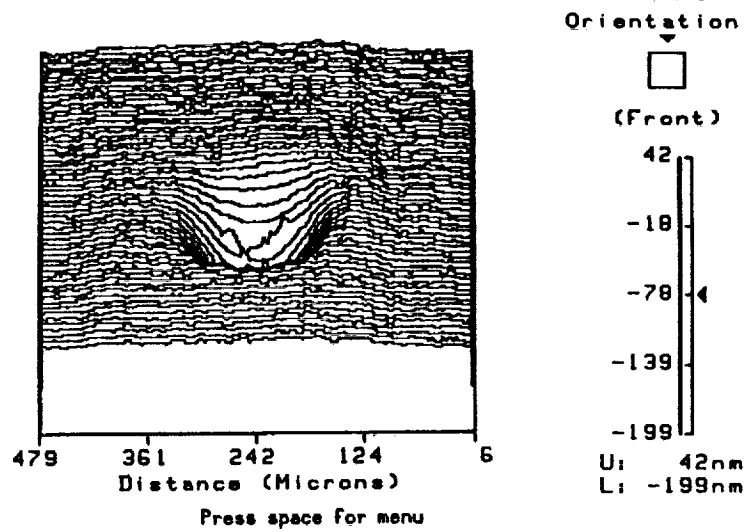


Figure 12 Residual surface defect left in mandrel after measurement with the CMM.

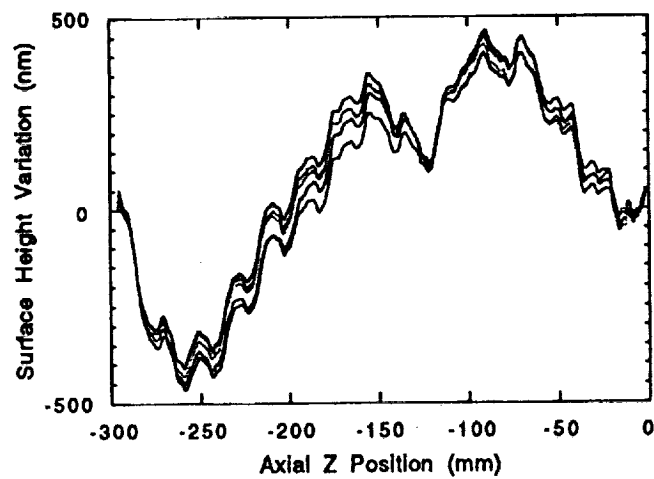


Figure 13 Surface height variation for the parabolic end of FS2 as measured with the LTP.

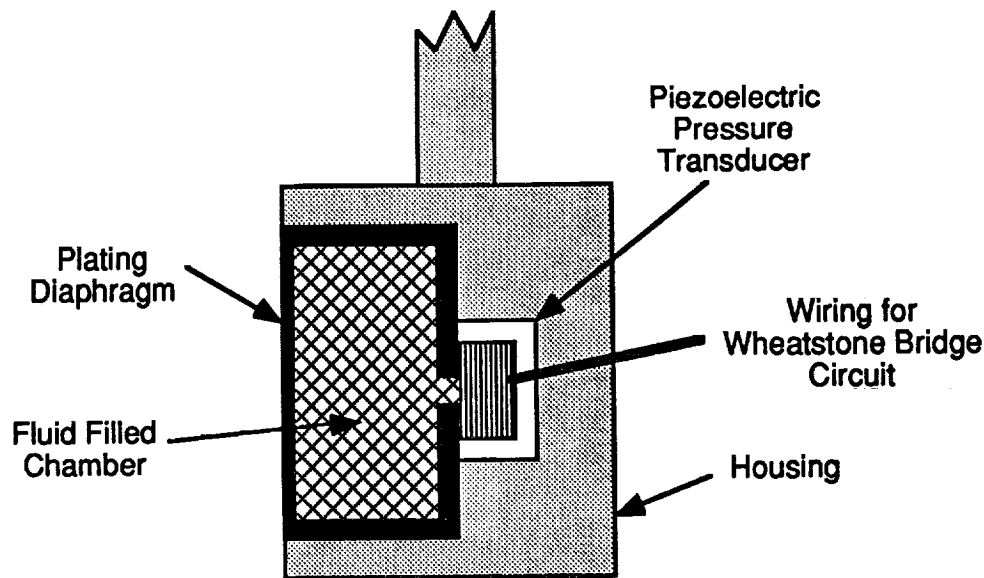


Figure 14 Stress monitor for the electroforming process.

REPLICATION PROCESS

After the mandrel is polished to the required finish and thoroughly cleaned, the electroless nickel is passivated by actively inducing the growth of a thin nickel oxide on the surface. This passivation is an electrolytic process and is controlled in such a manner to produce the desired stoichiometry. The mandrel is subsequently plated with an approximately 100-nm-thick layer of gold by either vapor or electrochemical deposition. This gold layer ultimately replicates the optical profile and is the reflection surface. Over the gold layer, a special stress-free nickel shell is electroplated to approximately 1 mm thick. The stress of the electroformed nickel is monitored with a custom stress monitor that measures the plating stress with a diaphragm and a piezoelectric transducer. The stress monitor is shown schematically in Figure 14. As the nickel is simultaneously deposited on the mandrel and the diaphragm, the slight deformation of the diaphragm due to stress is magnified by the fluid chamber and is sensed by the transducer. The output from the piezoelectric is converted to a voltage with a bridge circuit and then input to a computer for process monitoring. The algorithm uses the plating current as the control variable and forces the plating to proceed in a state of zero stress. This ensures that the formed mirror shell will not deform when it is removed from the mandrel. To eliminate the edge effects from the polishing phase (the substrate is removed at a faster rate when the

polishing pad encounters a discontinuity in the surface), the mandrel is formed longer than the required optical surfaces. Therefore, the electroformed optic must be cut to the desired length before separation from the mandrel. The cutting process is performed with a thin diamond blade on a grinder attached to the DTM. When the length cuts are complete, the shell is removed from the mandrel with a cryogenic separation procedure. The differential expansion of the shell with respect to the mandrel allows for a small gap to form between the two when the inside of the mandrel is filled with liquid nitrogen. Once removed, the Wolter I x-ray optic is complete and ready for mounting and testing in a 100-meter-long vacuum tunnel retrofitted with an x-ray source and detector.

ACTIVE VIBRATION COMPENSATION

To improve the surface finish characteristics of the diamond-turned mandrel, active vibration compensation methods are being considered. In one scenario, the vibration of the mandrel is monitored in real time and this error signal is used to move the cutting tool to compensate [6]. The amplitude of the vibration that occurs during the precision diamond turning of optical components is typically small (less than 10 micrometers) and occurs at frequencies below 100 hertz. This type of motion can easily be compensated for by using a piezoelectrically driven tool servo [7,8]. The basic design of the servo is shown in Figure 15. The diamond turning process requires a significant stiffness for all components in the metrology loop (between the part and the cutting tool). Therefore, a ceramic piezoelectric actuator is the ideal choice for providing the tool motion. In Figure 15, the cutting tool is intimately mated to the piezoelectric ceramic stack with a preload provided by the spring steel flexures. This preload serves dual purposes. First, it provides the required mating force to ensure the closed loop stiffness. Also, the preload ensures that the operation of the servo will occur with the ceramic consistently in compression. This is to counteract the inertial forces encountered when the servo is operating at the higher bandwidths. These forces result from the relatively small, but significant, mass associated with the tool and the mounting flange. The ceramic material is very strong in compression but will only permit a small amount of tension before failure. Therefore, for longevity and repeatability of the servo mechanism, the compression preload is required.

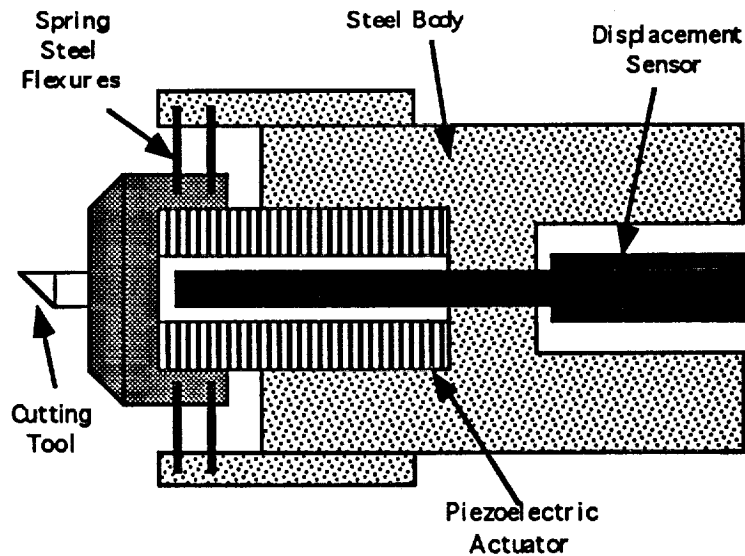


Figure 15 Cross section of a piezoelectric tool servo.

To compensate for the inherent machine vibration that occurs in the cutting process, a closed-loop control system must be utilized. This system consists of a real-time vibration sensor that feeds back to the tool servo. This sensor can be either an accelerometer or a displacement sensor, such as a capacitance gage. In this application, a non-contact capacitance gage will be required. The vibration of the mandrel will need to be monitored at both ends and the actual radial displacement at the cutting point will then be interpolated. This configuration is shown schematically in Figure 16. The sensors are placed at the ends of the mandrel and are referenced to the metrology frame (machine base). These signals are then processed in a control algorithm through a data acquisition system based on a personal computer. The other input to the system will be the current axial location of the cutting tool. The actual radial displacement at the cutting position can then be calculated, inverted and the output sent to the tool servo amplifier. This signal then provides tool motion that is equal and opposite of the vibration and negates its effect. The geometry of this particular application and the presence of cutting fluids and debris will make the implementation of this approach somewhat difficult. It is felt that the technique can be successfully utilized with proper engineering.

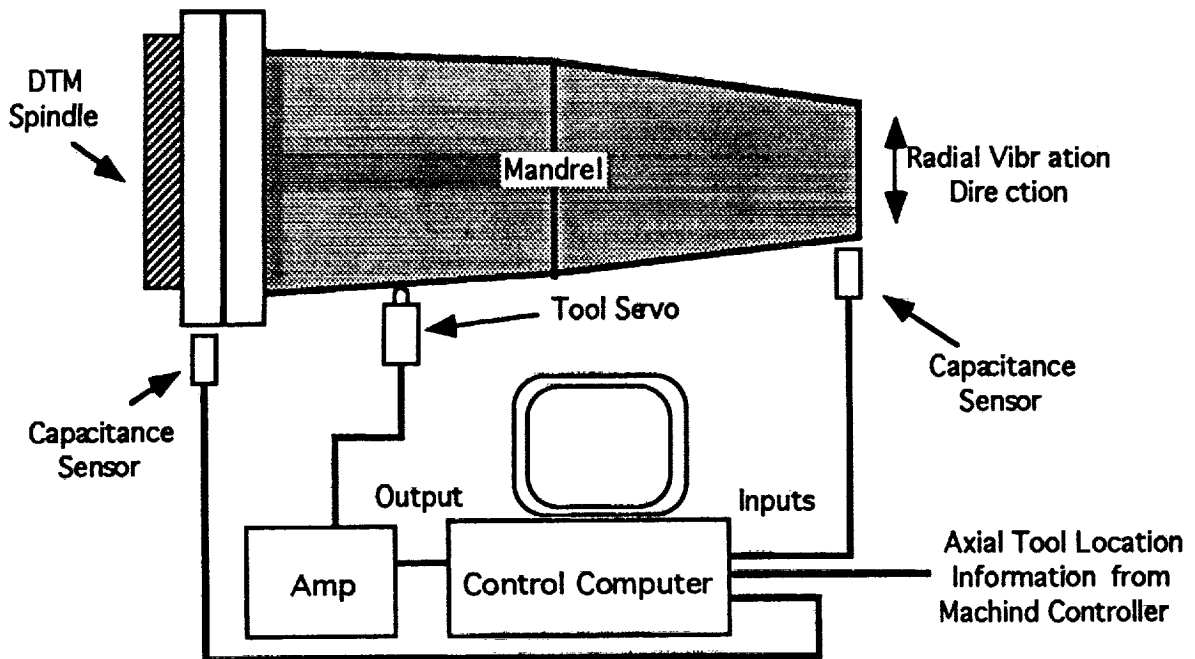


Figure 16 Schematic of the closed loop vibration control system.

CONCLUSION

The diamond turning and polishing operation to form the replication mandrels for the AXAF-S x-ray optics were quite successful. The program produced four full-scale mirror shells with dramatically improved results for each subsequent iteration. The final shell was successfully tested with x-rays and demonstrated 120 arc second resolution at the higher energies. The development program is considered a complete success and proved the technique as viable. However, several problems still exist in the processes and may be correctable for future mandrels. The primary areas of concern are the lack of a suitable thermal environment for the DTM and the inherent machine/part vibration during turning. The thermal environment is probably the main cause of the longer spatial frequency errors and will be corrected when the machine is moved to a new facility. The machine vibration will be corrected with passive damping and active compensation. The errors shown in Figure 13 with a wavelength of approximately 20 mm are related to the vibration problems and may be corrected with the vibration control measures and the closed-loop tool servo system.

ACKNOWLEDGEMENTS

This program was completed with the assistance of numerous individuals at Marshall Space Flight Center. The sheer number of people involved precludes giving individual recognition to all involved. The author in no way claims the results of this program as an individual achievement. However, several individuals whose work is reported here in detail should be recognized. The mandrel design and fabrication was facilitated by Bruce Weddendorf, Scott Hill, Janet Washington and John Redmon, Sr. The diamond turning was completed with the assistance of Carroll Black. The polishing and metrology was done in collaboration with Dave Lehner, Charlie Griffith, Raj Khanijow, Darryl Evans and Tom Kester. The mirror development program was managed by Robert Rood, James Bilbro and Charles Jones. The primary contributor to the development of the replication process was Darell Engelhaupt of the University of Alabama in Huntsville.

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